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Published in:

Proceedings of the 5th International Seminar on ORC Power Systems

Publication date:

2019

Document Version

Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):

Meroni, A., Geiselhart, M., Ba, W., & Haglind, F. (2019). Preliminary Design of Radial-Inflow Turbines for Organic Rankine Cycle Power Systems Considering Performance and Manufacturability Aspects. In S. Karellas, & E. Kakaras (Eds.), *Proceedings of the 5th International Seminar on ORC Power Systems* [57] National Technical University of Athens.

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PRELIMINARY DESIGN OF RADIAL-INFLOW TURBINES FOR ORGANIC RANKINE CYCLE POWER SYSTEMS CONSIDERING PERFORMANCE AND MANUFACTURABILITY ASPECTS

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ABSTRACT

In order to make organic Rankine cycle power systems economically feasible, it is essential to find a reasonable trade-off between the performance and the initial cost of system. In this context the expander plays an important role. High performance is often the main target in the preliminary design of the expander; however, ease of manufacturing and competitive cost might similarly contribute to a successful solution. The design of expanders for high efficiency and manufacturability is an unexplored field in organic Rankine cycle power systems.

In this paper, we propose a multidisciplinary approach to perform the preliminary design of radial-inflow turbines for organic Rankine cycle power systems, considering both performance and manufacturability aspects. The suitability of a turbine design is evaluated using two figures of merit: a manufacturability indicator and the turbine total-to-static efficiency. A mean-line model, estimating the turbine performance, is coupled to a model for the generation of a preliminary three-dimensional turbine geometry. In this way, the turbine performance and its manufacturability, predicted from the turbine geometry, can be simultaneously evaluated. A multi-objective optimization is then performed using the integrated design model to optimize both the turbine efficiency and manufacturability by varying the decision variables related to its geometrical and fluid-dynamic characteristics.

In order to show its relevance in a practical application, the method is applied to two radial-inflow turbines cases: a state-of-the-art turbine using air and a turbine using the working fluid Novec 649 for a heat recovery application. The results indicate that there exists a trade-off between turbine performance and manufacturability, and that it is possible to develop turbine solutions with similar values of efficiency with improved manufacturability indicator by up to 14-15 %.

1. INTRODUCTION

The current technological limits of organic Rankine cycle (ORC) power systems are extending towards small-to-micro scale applications (<100 kW). However, a major barrier for a full deployment of the ORC technology is the lack of cost-effective solutions, which would result in a more attractive specific cost and payback time. Thanks to their compact size, high specific work, high efficiency and low investment cost compared to the other expander technologies, radial-inflow turbines (RITs) are often selected for small-to-micro scale applications. The aerodynamic design of such machines is a challenging task and

is paramount to achieve highly efficient turbines. Concurrently, the commercial success of such solution is also determined by other factors beyond the aerodynamic performance, requiring a fully integrated, multidisciplinary approach.

Some authors have adopted a multidisciplinary approach to design RITs for turbochargers and micro-turbines, improving the aerodynamic performance, stress limitations and weight of the turbine (Mueller *et al.*, 2012; Fu *et al.*, 2012; Deng *et al.*, 2018). Recently, Odabae *et al.* (2016) optimized a 7 kW RIT for an ORC system by maximising the total-to-static efficiency while reducing the rotor thrust at hub, showing a possible improvement of about 2 % in both objective functions. When it comes to develop a cost-effective solution, manufacturing aspects become of primary concern. In general, design for manufacturability is a key aspect in the development of turbomachinery components. In this respect, Chaves-Jacob *et al.* (2011) proposed a manufacturability indicator which is representative of the difficulty to manufacture a certain turbomachinery impeller. Although different authors have addressed the issue to design and optimize RITs in a multidisciplinary context, there are no previous works addressing the interplay between manufacturability and turbine performance in the ORC field.

The objective of this paper is to present an approach to perform the preliminary design of radial-inflow turbines for organic Rankine cycle power systems, considering both performance and manufacturability aspects. The suitability of a turbine design was evaluated using two figures of merit: the manufacturability indicator proposed by Chaves-Jacob *et al.* (2011) and the turbine total-to-static efficiency. A mean-line model, estimating the turbine performance, was coupled to a model for the generation of a preliminary three-dimensional turbine geometry. A multi-objective optimization was performed using the two aforementioned models to optimize both the turbine efficiency and manufacturability by varying the decision variables related to its geometrical and fluid-dynamic characteristics. The method was then applied to two radial-inflow turbines cases: a state-of-the-art turbine using air and a turbine using the working fluid Novec 649 for a waste heat recovery application.

The paper is structured as follows: Section 2 presents the methods, Section 3 presents the results, and Section 4 presents the conclusions of the work.

2. METHODS

2.1 Turbine preliminary design

The preliminary design and performance estimation of RITs was based on the mean-line model developed by Meroni *et al.* (2018), which was validated within $\pm 3\%$ -points in total-to-static efficiency using the data at the design point of six high-pressure ratio RITs. The turbine total-to-static efficiency was the performance indicator of the preliminary turbine design, defined as

$$\eta_{ts} = \frac{h_{01} - h_{06}}{h_{01} - h_{6,is}} \quad (1)$$

where h_{01} and h_{06} are the total specific enthalpies at the turbine inlet and outlet, and $h_{6,is}$ the static specific enthalpy considering an isentropic process from the inlet to the outlet. The generation of a preliminary three-dimensional geometry for the nozzle and the rotor blades was performed based on the method proposed by Aungier (2006) using the mean-line geometry information. The rotor hub and shroud contours were constructed using a circular-arc and a power-law relation, respectively. The shroud and hub wrap angle distributions were defined as a polynomial function of the meridional coordinate, and the corresponding blade angle distributions in meridional direction were computed using polar and trigonometric relations. The full 3D rotor geometry was then constructed by transforming the polar coordinates into Cartesian. The method proposed by Aungier (2006) was also tested with the original profiles the turbine described by Jones (1996) and Sauret (2012) to check its correct implementation. The generation of the three-dimensional geometry using the aforementioned method is a key step to estimate the manufacturability of the turbine.

Table 1: ORC unit modelling conditions

Parameter	Value
Hot fluid	thermal oil
Hot fluid T_{in}	260 °C
Hot fluid T_{out}	220 °C
Hot fluid \dot{m}	0.7548 kg/s
Boiler pinch point	10 °C
Condenser fluid	water
Condenser T_{in}	40 °C
Condenser ΔT	5 °C
Condenser pinch point	5 °C
Turbine PR_{max}	4.5
Turbine η_{mec}	0.97
Pump η_{is}	0.7
Pump η_{mec}	0.97

Table 2: Preliminary design parameters for the air and ORC turbines

Parameter	Units	Air	Novec 649
\dot{m}	kg/s	0.33	0.5640
T_{01}	K	1056.5	388.4
p_{01}	kPa	580.4	450
p_6	kPa	94.7	100
U/C_0	-	0.692	0.7
N	rpm	106588	31302
r_{6s}/r_4	-	0.632	0.665
r_{6h}/r_{6s}	-	0.413	0.444
R_{is}	-	0.56	0.58
Z_r	-	16	14
Z_s	-	19	17
η_{ts}	-	0.851	0.845
\dot{W}	kW	121	6.55

2.2 Estimation of the turbine manufacturability

A turbine impeller is nowadays manufactured using five-axis machining, where flank milling is the preferred process to cut the production costs. Chaves-Jacob *et al.* (2011) explained that the two main manufacturing difficulties in flow passage roughing and flank milling are the flexion of the tool and workpiece, and the geometric tool path error. The former difficulty is due to the blade forces generated between the tool and workpiece while the latter is produced by the interference between the tool and the surface and is related to the twist of the intrados and extrados of the blades. This work employs the manufacturability indicator proposed by Chaves-Jacob *et al.* (2011), which aims to relate the impeller manufacturability to the two aforementioned problems via key geometrical indicators. The manufacturability indicator is defined as follows:

$$I_{man} = \frac{O}{4} + T_{max} + T_{av} \quad (2)$$

$$O = \frac{L_{min}}{D_{max}} \quad T_{max} = \begin{cases} \frac{\tau_{max}}{25} & \text{if } \tau_{max} \leq 25^\circ \\ 1 & \text{if } \tau_{max} > 25^\circ \end{cases} \quad T_{av} = \begin{cases} \frac{\tau_{av}}{20} & \text{if } \tau_{av} \leq 20^\circ \\ 1 & \text{if } \tau_{av} > 20^\circ \end{cases} \quad (3)$$

The parameter O is the overhang indicator, expressing the minimum tool overhang required to machine the blades. This parameter covers the flexion problem caused by the use of thin, long tools. The parameter T_{max} is the indicator of the maximum blade twist τ_{max} , and T_{av} is the indicator of the average blade twist τ_{av} . The twist is defined as the difference in the angles of the hub and shroud normals along the same rule. Both τ_{max} and τ_{av} are related to the geometrical interferences arising in flank-milling ruled, twisted surfaces. A value of I_{man} in the order of magnitude of 3 indicates a high machining effort due to tool/workpiece flexion and geometrical errors while a low value, in the order of magnitude of 1, indicates that the aforementioned sources of machining difficulty do not affect the actual machining process.

2.3 Case studies

This work employed two case studies, which were used to assess the change in efficiency and manufacturability of the turbine geometry. The first case study is a high-pressure ratio turbine operating with air and described by Jones (1996) and Sauret (2012).

The second test case is an ORC turbine, whose boundary conditions come from the ORC system optimization using the model by Andreasen *et al.* (2014), which was validated for pure fluids within 3.27 % by comparison with similar results in the literature. Table 1 lists the conditions considered for the design of the ORC system. A heat source, represented by a thermal oil loop, is cooled from 260 °C to 220 °C and powers the ORC systems. A maximum limit of 4.5 in the turbine pressure ratio was imposed to avoid

designing a supersonic, converging-diverging nozzle, hence ensuring high levels of efficiency even at off-design operation due the variability of the heat source. The turbine efficiency at the design point was estimated using the performance charts developed by Perdichizzi and Lozza (1987). The working fluid Novec 649 was selected after screening different working fluid candidates from REFPROP (Lemmon *et al.*, 2002) based on the following criteria: (i) zero ozone depletion potential; (ii) low global warming potential (< 150); (iii) no toxicity; (iv) no flammability; (v) thermal stability without decomposition up to 300°C (3M, 2009); (vi) high cycle net power output and turbine efficiency ($> 80\%$); (vii) acceptable values of turbine rotational speed and rotor diameter. The choice of the working fluid Novec 649 for ORC systems has also been made in other studies (Cogswell *et al.*, 2011; Reinker *et al.*, 2015; Bonk *et al.*, 2017).

Table 2 lists the design conditions obtained for the two turbine case studies and their performance using the mean-line model.

2.4 Multi-objective turbine optimization

A multi-objective optimization was performed on the two reference turbines to improve simultaneously the values of efficiency and manufacturability indicator. The optimization problem was formulated as follows:

$$[\min(-\eta_{ts}), \min(I_{man})] = f(\bar{X}) \quad \text{and} \quad \bar{X} = \left[\frac{U}{C_0}, N, \frac{r_{6s}}{r_4}, \frac{r_{6h}}{r_{6s}}, R_{is}, Z_r, Z_s \right] \quad (4)$$

where U/C_0 is the velocity ratio, N the rotational speed, r_{6h} and r_{6s} the rotor exit hub and shroud radii, r_4 the tip radius, R_{is} the isentropic degree of reaction, Z_r and Z_s the number of rotor and nozzle blades, respectively. The optimization was performed using turbine geometric and fluid-dynamic constraints to achieve a reasonable design according to the indications by Rohlik (1968), Aungier (2006), Moustapha *et al.* (2003) and Perdichizzi and Lozza (1987).

3. RESULTS AND DISCUSSION

3.1 Optimal designs

Figure 1 shows the Pareto fronts of the optimization for the air and the Novec 649 turbines. Five points in the Pareto front, from (i) to (v), were selected and analyzed. The Pareto front of the air turbine, illustrated in Fig. 1(a), indicates that the total-to-static efficiency varies from approximately 86.5 % to 79.5 %, with a relative and absolute change of about 8.1 % and 7 %-points, respectively. Better manufacturability can be achieved from the point (v) to (i), at the expenses of a lower efficiency. In this case, the manufacturability indicator changes from 2.35 to 1.42, suggesting an improvement of about 39.6 % in the turbine manufacturability. The Pareto front obtained in Fig. 1(a) is constrained at low values of efficiency (point (i)) due to the onset of choking conditions in the rotor blades while it is constrained at high value due to the maximum limit of -60° in the rotor exit shroud blade angle, in order to avoid the occurrence of excessive flow separation. Fig. 1(b) suggests that a larger variation in efficiency and manufacturability is obtained for the ORC turbine. The efficiency is in the range 85.7 % to 71.4 %, with a relative and absolute change of up to 16.7 % and 14.3 %-points, respectively. The manufacturability indicator is in the range 2.76 to 0.95, suggesting an improvement in manufacturability up to 65 % from point (v) to point (i). The Pareto front of the Novec 649 turbine is limited at point (v) due to the rotor exit blade constraint, close to -60° , and at point (i) due to onset of choking in the rotor as well as the minimum values of blade twist, which is close to zero.

When the manufacturability indicator decreases in the Pareto front, the total-to-static efficiency of the optimal solutions reduces. Figure 2(a) depicts the breakdown of losses of the five points in the Pareto front for both the air and ORC turbines. The results indicate that the change in efficiency for the air turbine is dominated by the nozzle losses, which increase when the rotor has a low manufacturability indicator (easy to manufacture) to maintain the specified total-to-static pressure ratio through the stage. This aspect is also present in the breakdown of losses of the ORC turbine, although the main responsible for

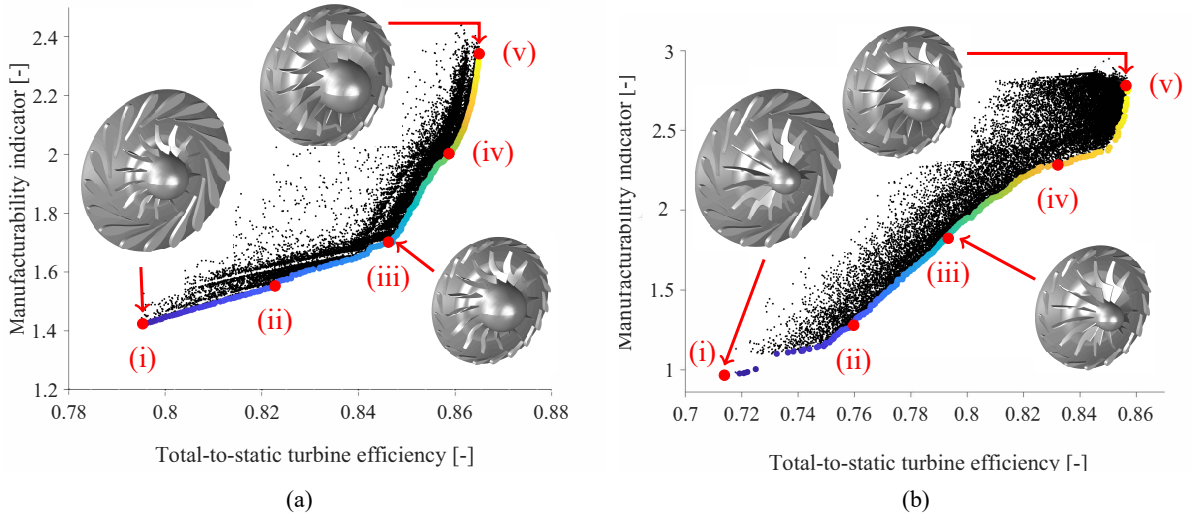


Figure 1: Pareto Front of the optimal solutions in terms of total-to-static efficiency and manufacturability indicator for (a) the air turbine and (b) the Novec 649 turbine

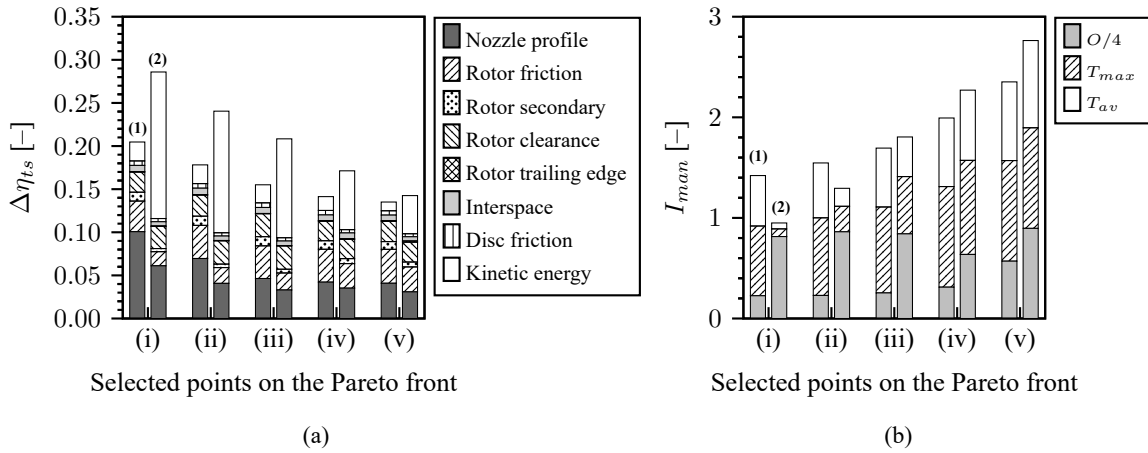


Figure 2: Breakdown of the turbine losses and manufacturability indicator for the (1) Air and (2) Novec 649 turbine designs

the drastic reduction in efficiency is the increasing contribution of the kinetic energy loss for decreasing values of the manufacturability indicator. The main explanation for this trend is that, in order to achieve a rotor shape easy to manufacture, the velocity triangles change shape, reducing the work extraction and yielding a higher value of the exit kinetic energy. From the manufacturability viewpoint, the key parameter driving the change of I_{man} along the Pareto front is the blade twist. Figure 2(b) highlights that, when the turbine is optimized for a better manufacturability (from point (v) to (i) in the Pareto front), the overhang is similar in all cases whereas the maximum and average values of blade twist reduce significantly, reaching values close to zero in the case of the ORC turbine.

Figure 3(a) shows the change in the maximum and average values of blade twist as a function of the blade turning in the two Pareto fronts. The turbine rotor blades featuring a low turning (or small exit angle) are characterised by a low value of blade twist. Note that the air turbine solutions with values of twist and blade turning close to zero are infeasible due to the presence of a choked rotor. Figure 3(b) shows that the efficiency and manufacturability indicator of the Pareto front solutions are also related to the blade turning. When the turbine is optimized for maximum efficiency, the work extraction is maximized and so is the blade turning and twist. However, a large turning results in a high twist, and therefore a high

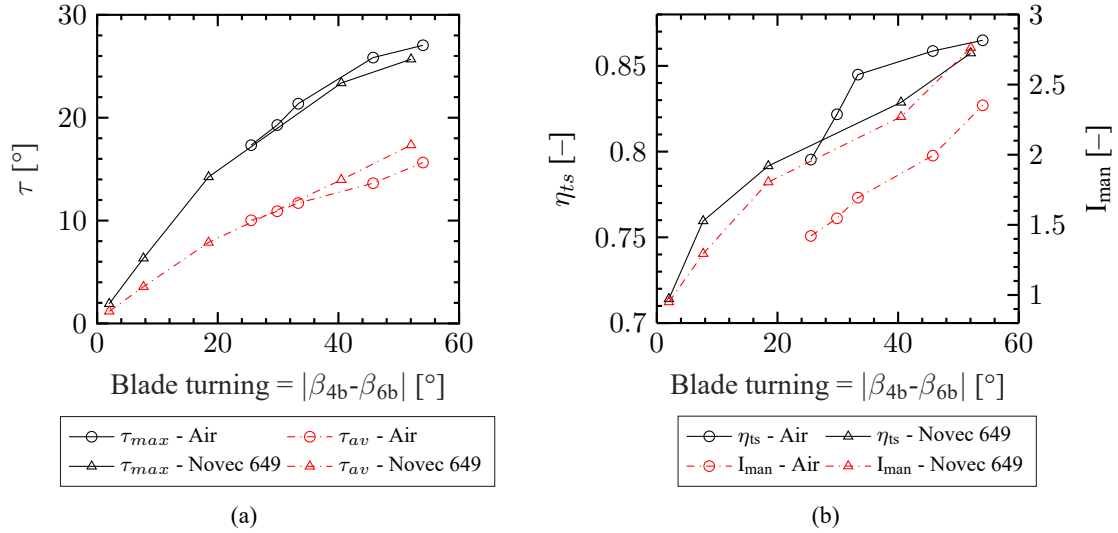


Figure 3: (a) Maximum and average blade twist, (b) efficiency and manufacturability indicator as a function of the blade turning for the air and Novec 649 turbines

value of the manufacturability indicator.

4. CONCLUSIONS

This paper presented an approach to perform the preliminary design of radial-inflow turbines considering at the same time turbine performance and manufacturability aspects. The preliminary design method couples a mean-line model, for the estimation of the turbine performance, to a three-dimensional tool, for the generation of a preliminary turbine geometry. A multi-disciplinary optimization was then performed using the combined model by simultaneously maximizing the turbine total-to-static efficiency and minimizing the manufacturability indicator. The method was applied to the preliminary design of two turbine test cases: a high-pressure ratio air turbine and a turbine for an Organic Rankine cycle system using the fluid Novec 649. The results of the two Pareto front solutions highlight a trade-off between the turbine total-to-static efficiency and the manufacturability indicator. The results indicate that the turbine manufacturability can be improved by up to approximately 65 % at the expenses of a reduction in the turbine efficiency by up to 14.3 %-points. The designs in the Pareto front region close to the maximum turbine efficiency could also be considered to develop turbine solutions with similar values of efficiency but improved manufacturability indicator by up to 14-15 %. The evolution of the design points in the Pareto front is linked to the change of the blade turning angle, which in turn affects the work extraction and the blade twist. This results in a change of the values of efficiency and manufacturability indicator. The method and results presented in this work constitute the first step towards the development of cost-competitive radial-inflow turbine for ORC power systems. Future work includes to extend the method presented in this paper by adding considerations related the manufacturing time, enabling to reveal the trade-off between the performance and investment cost of the expander.

NOMENCLATURE

$C_0 = \sqrt{2(h_{01} - h_{6,is})}$	spouting velocity	(m/s)
D	distance	(m)
I_{man}	manufacturability indicator	(-)
L	blade length in span-wise	(m)
\dot{m}	mass flow rate	(kg/s)
O	overhang indicator	(-)
p	pressure	(Pa)

PR	pressure ratio	(-)
r	radius	(m)
R	degree of reaction	(-)
T	temperature; twist indicator	(K);(-)
U	rotor tip speed	(m/s)
Z	number of blades	(-)
\dot{W}	turbine power output	(W)
β_b	blade angle in meridional direction	($^\circ$)
η	efficiency	(-)
τ	blade twist	($^\circ$)

Subscripts

01	turbine inlet total condition
4	rotor inlet static condition
6	turbine exit static condition
h	hub
av	integral average
in	inlet
is	isentropic
max	maximum
mec	mechanical
min	minimum
out	outlet
r	rotor
s	stator; shroud
ts	total-to-static

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ACKNOWLEDGEMENTS

The research work was conducted within the frame of the THERMCYC project funded by Innovation Fund Denmark, The Danish Council for Strategic Research in Sustainable Energy and Environment.